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Technical Report

# RIDE SEVERITY PROFILE FOR EVALUATING CRAFT MOTIONS

by


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**NSWCCD-80-TR-2015/002** Ride Severity Profile for Evaluating Craft Motions

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# SYMBOLS, ABBREVIATIONS, AND ACRONYMS

| | |
|---|---|
| A | vertical peak-acceleration |
| $A_{1/10}$ | average of the 1/10th highest peak accelerations |
| $A_{1/100}$ | average of the 1/100th highest peak accelerations |
| $A_{1/N}$ | average of the 1/Nth highest peak accelerations |
| ft | feet |
| g | acceleration due to gravity |
| LCG | longitudinal center of gravity |
| N | number of wave impacts |
| NSWCCD | Naval Surface Warfare Center Carderock Division |
| RMS | root mean square |
| RMQ | root mean quad |
| sec | second |

## ADMINISTRATIVE INFORMATION

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## SUMMARY

This report presents a new approach for presenting ride severity data for marine craft. Key assumptions and algorithms for processing acceleration data are summarized, and interim ride quality criteria associated with human comfort and performance are presented that define broad transition zones in a new ride severity profile format.

## INTRODUCTION

### Background

A collaborative research initiative is being pursued that integrates an automated data collection system onboard high-speed planing craft to better understand the operational demands on propulsion, navigation, and communications systems. The system being developed by the Navy is adapted from the U.S. Army's in-theatre black box data acquisition system for collecting automotive performance and ballistic data [1]. The Navy system hardware also includes accelerometers that will provide valuable feedback for better understanding the environmental demands and effects of wave impacts on crew comfort and performance.

### Objective

The objective of this report is to introduce a new way of presenting acceleration results as a ride severity profile that displays peak acceleration data with interim criteria for describing subjective levels of human comfort and performance.

### Approach

The recorded acceleration data will be processed by the black box system using *StandardG* [2]. *StandardG*[1] is a software package that applies principles of response mode decomposition to separate rigid body motions in the raw acceleration signal from flexural vibrations in the vicinity of a gage [3, 4]. Rigid body peak acceleration is a measure of the maximum load amplitude caused by a wave impact [5], so it is a useful metric for wave impact severity.

During craft operations the monitoring system will compute and tabulate rigid body peak accelerations caused by each wave encounter. The peak accelerations will be plotted in a semi-logarithmic format and labeled with transition zones that correspond to different levels of subjective human comfort and performance.

The following sections describe the new plotting format for peak accelerations and why the transition zones are presented as interim criteria.

---

[1] The *StandardG* algorithm for extracting rigid body peak accelerations from acceleration data is available for evaluation from John Zseleczky, P.E., Branch Head, Hydromechanics Lab, U.S. Naval Academy, johnz@usna.edu, (410) 293-5102. It can be run using MATLAB™ or Octave™ software.

# DATA DISPLAY FORMAT

## Wave Impact Severity

Several key parameters can be used to describe what are typically perceived as unpleasant or uncomfortable experiences (i.e., rides) in planing craft. Fore-aft rigid body decelerations can cause individuals to lurch forward, much like the hard application of brakes in an automobile, and extreme pitch and roll rates can lead to uncomfortable motions that result in whiplash-like dynamics, especially in the neck and spine regions. Motions in a transverse (i.e., port-starboard) direction must also be considered because of the different direction of deceleration forces (e.g., beam and quartering seas) when impacting a wave. All of these distinguishing attributes of a ride determine the overall quality or roughness of the ride. When impact accelerations and rates of rotation are low, the comfort level will typically be perceived as better (neglecting motion sickness) and the crew will more likely be able to perform their functions without decreased proficiency over time.

The most common parameter used to describe ride severity has been the vertical rigid body acceleration (i.e., heave acceleration) [6]. The measure of peak vertical accelerations tend to be a better discriminator because they vary over a larger range than other metrics like the root-mean-square (RMS) or root-mean-quad (RMQ), or other parameters like roll or pitch. As accelerations increase with speed and wave height, the discomfort experienced can rapidly increase, leading to extreme discomfort, especially for seated personnel.

Acceleration values are typically based on the same zero reference where -1 g is the acceleration due to gravity. The fundamental unit of acceleration is length per time-squared (e.g., ft/sec$^2$), but values given in most publications are normalized for convenience by dividing by the acceleration due to gravity (e.g., 32.2 ft/sec$^2$).

The automated monitoring system will use rigid body peak accelerations in the vertical direction as the measure of ride severity.

## Data Processing

There are three important steps that must be incorporated in the automated monitoring system to process the raw acceleration data. First, the raw signal must be converted from volts to engineering units of acceleration. Second, the raw acceleration signal must be demeaned – that is, the average of all digitized data points in the signal must be zero. This shifts the vertical axis of the acceleration record to zero. Third, the demeaned acceleration record must be low-pass filtered to remove flexural vibrations in the vicinity of the accelerometer. All acceleration data examples presented in the next sections were processed using these three steps.

## Peak Accelerations

Figure 1 shows a typical plot of acceleration versus time recorded during a seakeeping trial in head seas. Each spike in the record represents a wave encounter. The accelerometer was located on the deck oriented vertically (i.e., perpendicular to the deck). The red curve is the

unfiltered acceleration signal that contains rigid body accelerations and accelerations of vibrations where the gage was mounted. The black curve is the estimated rigid body acceleration curve computed by *StandardG* using a low-pass filter. The black circles are the rigid body peak accelerations greater than the RMS value of the signal extracted by the *StandardG* algorithm.

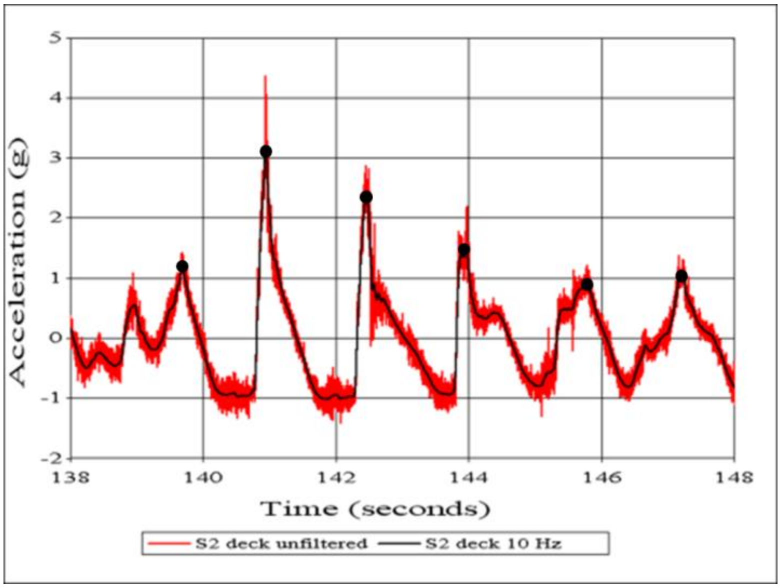


Figure 1. Typical Recorded Acceleration Data

Two data plots created by the *StandardG* algorithm are shown in Figure 2. The plot on the left shows the acceleration record as a function of time where just the rigid body peak accelerations greater than the RMS value are plotted. The plot on the right shows the same 154 peak acceleration values, reordered largest to smallest and plotted from left to right by peak number. The largest peak acceleration is peak number 1, and the smallest is peak number 154.

## Cumulative Distribution Plot

In Figure 3 the plot on the left is a set of 353 peak accelerations from a different acceleration record. The curve on the right is the cumulative distribution plot of all the peak accelerations. The abscissa value at each point on the curve is the percentage of peaks *less* than the ordinate peak acceleration. For example, the plot indicates that approximately 80 percent of the peaks are less than 1.8 g.

The peak accelerations can also be plotted in a cumulative distribution format for the percentage of peaks *greater* than the ordinate value. This is illustrated in Figure 4 using the same peak acceleration values shown in Figure 3. The ordinate axis is the peak acceleration of each wave impact, and the abscissa value is the percentage of peaks *greater* than or equal to the ordinate value. On the right side of Figure 4 this data is plotted with a logarithmic abscissa scale rather than a linear scale.

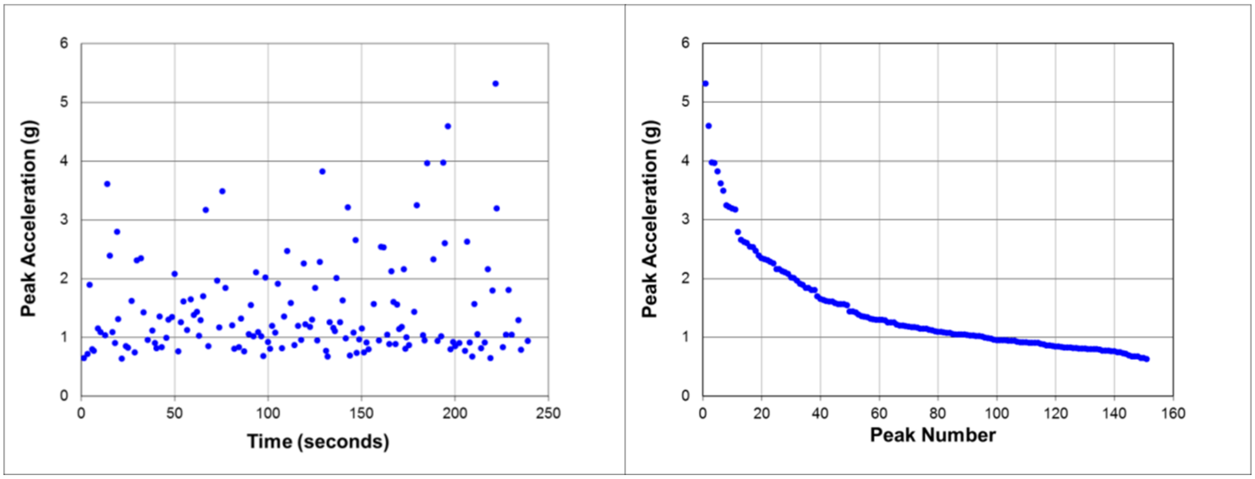


Figure 2. Peak Accelerations versus Time and Peak Number

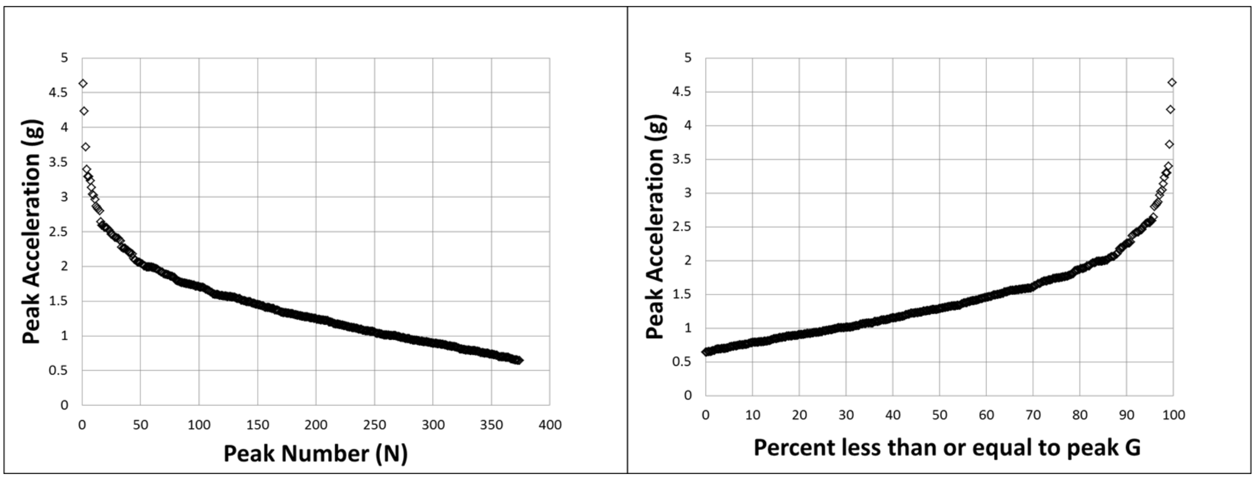


Figure 3. Plots of Peak Acceleration and Cumulative Distribution

The plot on the right in Figure 4 is referred to as a semi-log plot where one scale is logarithmic and the other is linear. This format has the benefit of clearly displaying the data points at and above the top 1-percent and ten-percent of peaks. These ranges of peak accelerations are the values used by naval architects to compute the average of the highest one percent of peak accelerations, $A_{1/100}$, and the average of the highest ten percent of peak accelerations, $A_{1/10}$. For example, in Figure 4 the plot on the right shows that one percent of the data is greater than or equal to approximately 3.4 g. The peak values greater than 3.4 g are the ones used to compute $A_{1/100}$. Likewise, the plot shows that values greater than approximately 2.2 g are used to compute $A_{1/10}$. The importance of this visual relationship will be explained in the next section.

Another benefit of the semi-log plot is that it displays data with exponential relationships as straight lines. Deviations from a straight line (i.e., a knee in the curve) suggest other physical phenomena may be occurring that do not follow the same exponential trends. The preferred

format for displaying data by the automated craft monitoring system is the semi-log plot shown on the right side of Figure 4.

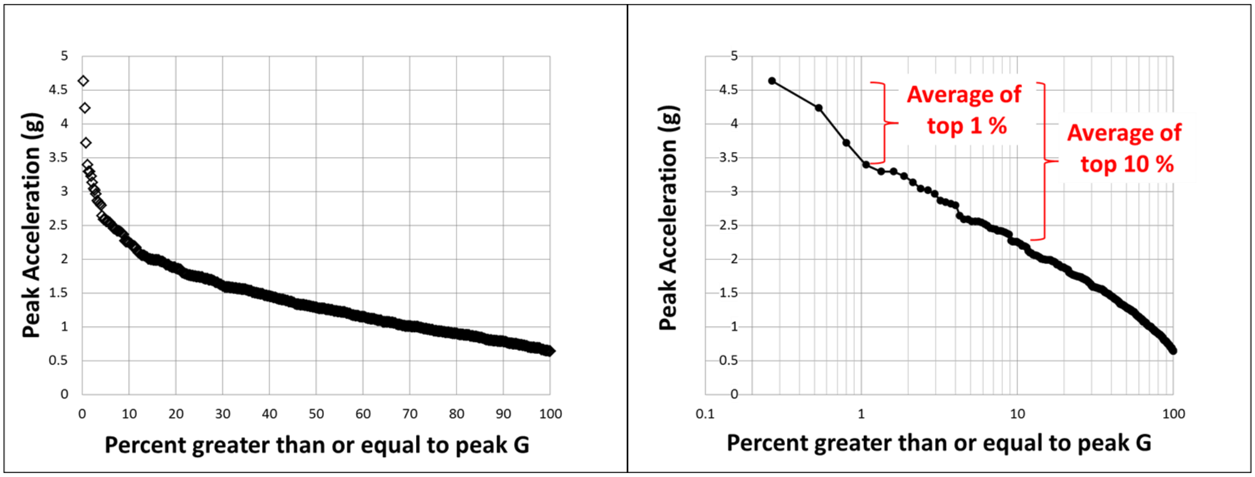


Figure 4. Linear and Logarithmic Scales for Same Data Plot

## Vertical Threshold

In the current version of *StandardG* the algorithm extracts and tabulates only those peak accelerations greater than the RMS value of the low-pass filtered acceleration signal. This was established as a standard approach to computing unambiguous $A_{1/N}$ values [2]. While the RMS vertical threshold does not necessarily have to be applied for presenting ride severity profiles for this application, as a matter of processing consistency, it is recommended that the *StandardG* algorithm be applied as written.

# INTERIM CREW COMFORT AND PERFORMANCE CRITERIA

## Modeling

Numerous historical references address tolerance limits for humans exposed to dynamic motions that can lead to injury or loss of performance. The literature for high-speed craft applications includes both vibration based models for repeated motions over time as well as impact models that account for the rate of acceleration application, the shape, and duration of single severe impacts [7]. Models have also been developed for use in impact injury design rules [8], but these detailed approaches are beyond the scope of the current investigation. The current need is to pursue a less rigorous quick-assessment approach that lends itself to easy implementation when combined with broadly defined performance criteria.

## $A_{1/N}$ Acceleration Values

Subjective crew comfort and performance criteria were first published in open literature in 1993 based on $A_{1/10}$ values recorded at the longitudinal center of gravity (LCG) of craft [9].

Table 1 lists the values along with generic descriptions of the effects of the ride on personnel. They were reported to be based on subjective feedback from naval crews following high-speed trials in different sea conditions.

The values listed in Table 1 should not be interpreted as fixed values that apply equally to all individuals in different craft or sea conditions, nor are they exact acceleration numbers that correspond precisely with specific comfort levels. People can exhibit large variations in their perceptions of the environment, and the tolerance of one person may not be consistent [10, 11]. An environment that is uncomfortable or fatiguing to one person may be judged comfortable and tolerable by another. For example, one individual may experience 1 to 2 hour limited performance after being exposed to $A_{1/10}$ equal to 1.5 g while another individual may experience similar effects at 2.0 g.

Table 1. 1993 Crew Comfort and Performance Criteria

| $A_{1/10}$ (g) at LCG | Effects on Personnel |
|---|---|
| 1.0 | Maximum for millitary function long term (over 4 hours) |
| 1.5 | Maximum for military function short term (1 - 2 hours) |
| 2.0 | Tests discontinued |
| 3.0 | Extreme discomfort |
| 4.0 | |
| 5.0 | Physical injury |
| 6.0 | Military crew under fire |

## Future Investigations

There has been no scientific study to corroborate or improve Table 1 values, but recent feedback from experienced test coxswains, test engineers, and naval architects suggests that the numbers are appropriate for defining broad ranges of possible effects (except for the 2.0-g value). The ranges of $A_{1/10}$ values presented in the next section are useful for the current application. Additional studies should be pursued that systematically investigate parameters and conditions affecting human performance and comfort in a wave impact environment [7].

## Interim Criteria

Table 2 provides descriptions of $A_{1/10}$ transition zones that build upon the 1993 values by adding generic descriptions based on feedback from skilled operators and occupants in numerous craft at various speeds and in different sea states[2]. The ranges of $A_{1/10}$ values in Table 2 serve as interim criteria until further detailed research can be performed. They are intended to characterize broad transitions zones useful for diverse populations of craft occupants.

[2] Information is contained in a limited distribution U.S. Navy report.

Table 2. Interim Transition Zones for Crew Comfort and Performance

| $A_{1/10}$ | Transition Zones |
|---|---|
| < 1.5 g | Conditions typically result in a comfortable ride with effective performance for 4 hours or more |
| 1.5 g - 2.0 g | Conditions may transition from a comfortable ride to a ride with limited discomfort |
| 2.0 g - 2.7 g | Conditions transition from a comfortable ride to a ride with discomfort and limited performance |
| 2.7 g - 3.2 g | Conditions transition from discomfort to the onset of extreme discomfort |
| 3.2 g - 5.5 g | Conditions transition from extreme discomfort to the onset of concern for personnel safety |
| 5.5 g - 6.0 g | Conditions transition from extreme discomfort and concern into potentially unsafe conditions with increased risk of safety mishaps |

There is no known causal relationship between the $A_{1/10}$ parameter and perceived comfort or the ability to perform mission functions with or without limitations. Its continued use as a metric for correlation with craft acceleration data is based on aligning an average acceleration value (e.g., $A_{1/10}$) with averaged descriptions of transition zones (i.e., averaged feedback from different people and operating conditions). In other words, as peak accelerations increase with increasing craft speed or wave steepness, a range of accelerations may correlate better with transition zones than a single parameter like the maximum peak acceleration in a data set.

## RIDE SEVERITY PROFILES

### Semi-log Data Plot

Figure 5 shows a display format of a ride severity profile. It combines the data shown in Figure 4 with crew comfort and performance zones as suggested in Table 2. The ordinate is the peak acceleration for each wave impact, and the abscissa is the percent of data *greater* than that peak acceleration. The shaded transitions from one color to another correspond roughly to the ranges listed in Table 2. This profile is recommended for automated craft monitoring systems because all data points for a given operational period are included in the plot without showing the time at which they occurred. Therefore, the display is appropriate for time periods as short as 5 minutes or as long as 5 hours or 5 days. The profile is not dependent upon speed, wave steepness, or craft heading, so the format is compatible with continuous data acquisition for operations at different speeds, different headings, and different wave heights. It provides a picture of the severity of all wave impacts encountered over time, but it does not indicate at what time the different peaks are encountered.

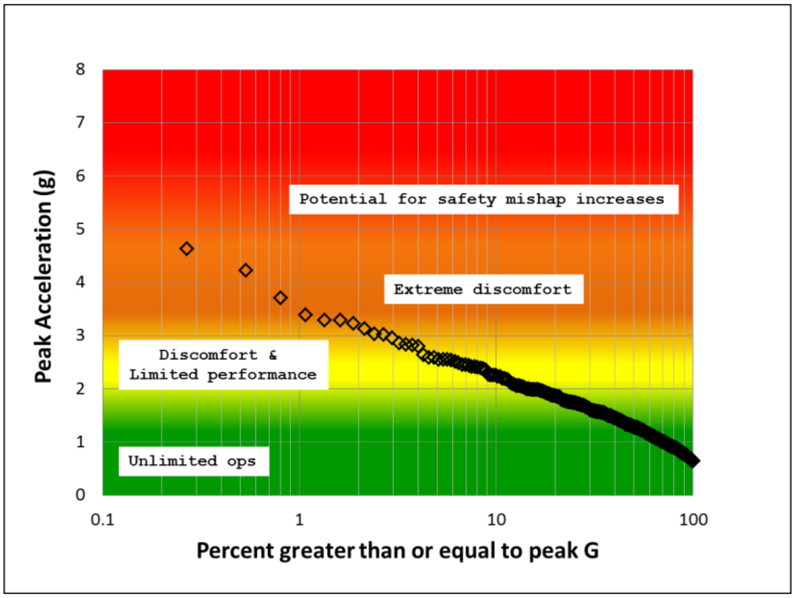


Figure 5. Notional Ride Severity Display Format

Peak accelerations for two different sets of data recorded during seakeeping trials are shown in Figure 6. It illustrates the easy visual display of two very different rides. The upper curve was a ride that included wave slams that were described as extremely uncomfortable (i.e., some peak accelerations in the orange zone) compared with another ride that was called an “easy day underway” (i.e., all peak accelerations in the green zone).

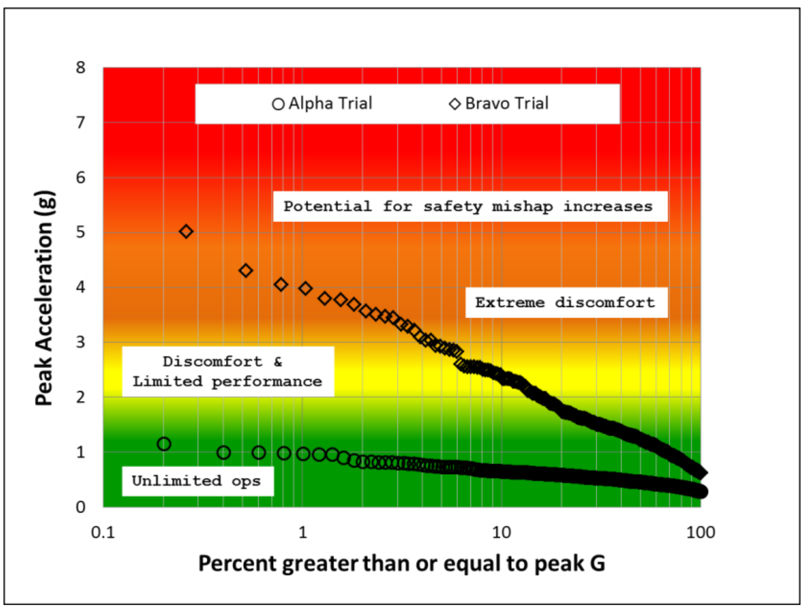


Figure 6. Ride Severity Profiles for Two Seakeeping Trials

## Observation

It is anticipated that the format of the ride severity profile will be useful in future investigations of human cognition in a wave slam environment. For example, in Figure 3 the data was from a seakeeping trial in head seas at high speed and a high sea state for approximately 10 minutes. It was reported to be an uncomfortable ride, but the data indicates that about 80 percent of the peak accelerations were less than 1.8 g, a level otherwise generally considered relatively comfortable. Over periods of time at relatively constant speed the random encounter of different wave heights shuffles low severity and higher severity impacts. The indication in this example is that just 20 percent of the random impacts above 1.8 g (shown in Figure 4) were sufficient for users to identify the ride as uncomfortable.

# CONCLUSIONS AND RECOMMENDATIONS

The format of the ride severity profiles shown in Figures 5 and 6 are easily adaptable for use in automated monitoring systems. It is recommended that recorded acceleration data be processed using the *StandardG* algorithm using the three data processing steps summarized herein. It is recommended that the processed data be plotted in the ride severity profile format. It is recommended that future studies be conducted to systematically investigate motion parameters (i.e., all degrees of freedom) and conditions that affect human performance and crew comfort in a wave impact environment. Until such studies are completed the transition zones for vertical accelerations listed in Table 2 can be considered useful as interim criteria for creating ride severity profiles.

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